W-boson production in spin-dependent global analysis

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✔ Usefulness of lepton-level asymmetries $A_L(y_\ell)$ in W boson production

✔ Implementation of NLO $A_L(y_\ell)$ in the global fits

Next-to-leading order (NLO) corrections in the analysis of parton distributions

- ✔ Required to make accurate predictions

- ✔ Would drastically slow calculations if straightforwardly implemented in the fit

Common solution: calculate the NLO cross section as

$$\sigma_{NLO} = K\sigma_{LO},$$

where

- ✔ the LO cross section σ_{LO} is updated in each call of the minimization subroutine

- ✔ the more complicated factor $K \equiv \sigma_{NLO}/\sigma_{LO}$ is updated every n calls (where n is a large number, e.g., $n \sim 10^3$)

K-factors in the spin-dependent fit

In the polarized case, the convergence of such procedure is questioned due to

- ✔ flexibility and indefinite sign of spin-dependent distributions $\Delta f(x, Q)$
- ✔ possible presence of radiation zeros ($\sigma_{LO} = 0$) in spin-dependent cross sections

An alternative method involves a complete calculation of σ_{NLO} in each call of minimization using Mellin transform *(M. Stratmann, W. Vogelsang, Phys. Rev. D64, 114007)*

❁ I will argue that the K-factors provide an efficient way to implement NLO corrections in polarized W boson production

$\Delta pp \to (W^{\pm} \to l\nu)X$:
asymmetry $A_L(y_\ell)$ with respect to the rapidity y_ℓ of the decay charged lepton *(P. N., C.-P. Yuan, NPB666, 3 (2003); ibid., B666, 35 (2003))*

$$A_L(y_\ell) \equiv \frac{\frac{d\sigma^{\vec{p}p}}{dy_\ell} - \frac{d\sigma^{\overleftarrow{p}p}}{dy_\ell}}{\frac{d\sigma^{\vec{p}p}}{dy_\ell} + \frac{d\sigma^{\overleftarrow{p}p}}{dy_\ell}}$$

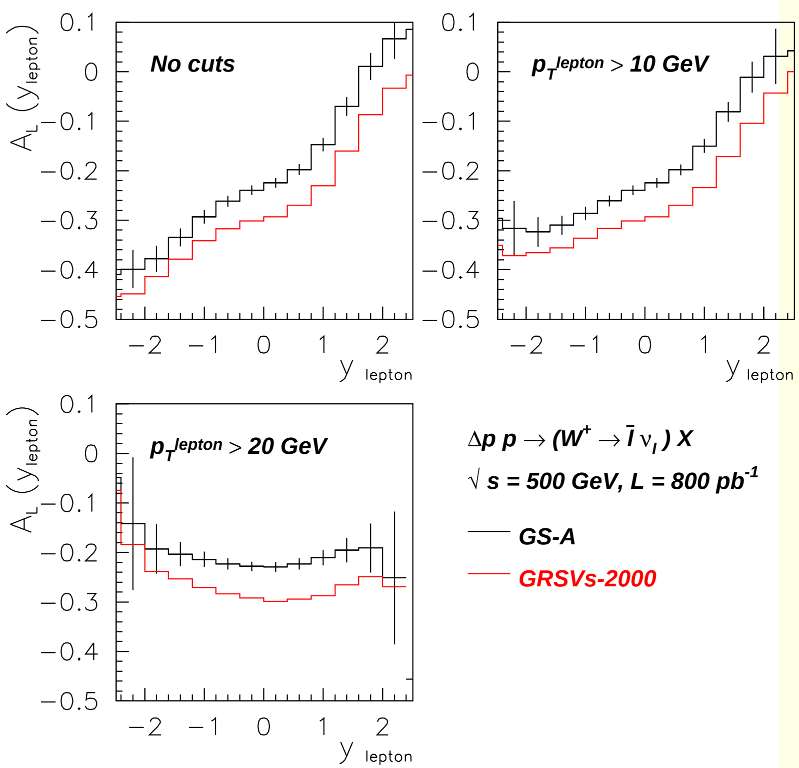
A better alternative to the commonly discussed single-spin asymmetry $A_L(y)$ with respect to the rapidity y of the W boson

- ✔ Directly measurable
- ✔ Not distorted by limited acceptance of RHIC detectors (while $A_L(y)$ is strongly distorted)
- ✔ Sensitive to different polarized parton distributions
- ✔ A fully differential $\mathcal{O}(\alpha_S)$ calculation with inclusion of W-boson decay and transverse momentum resummation exists in the form of a Monte-Carlo code

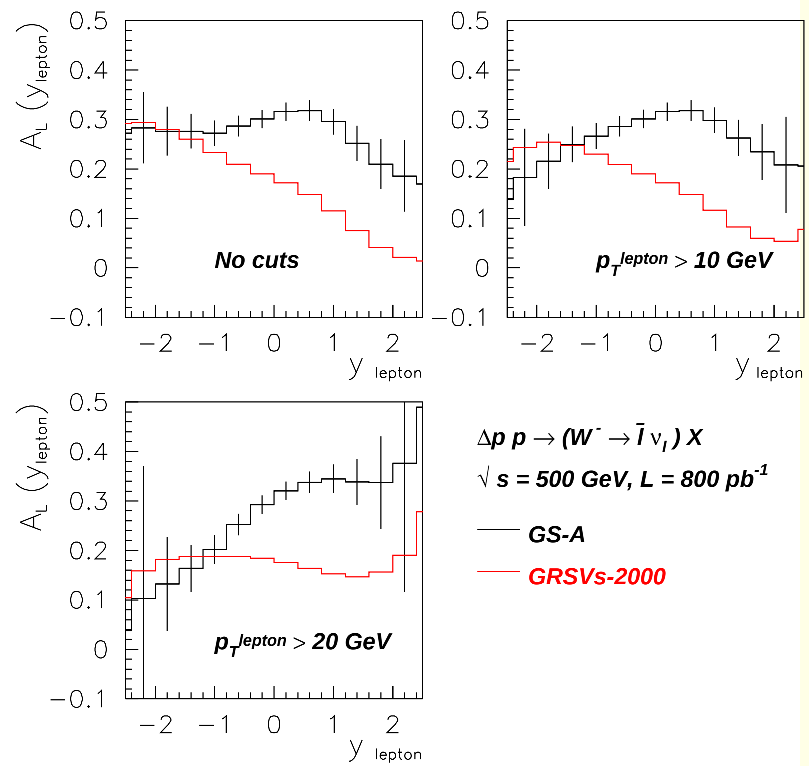
  (available at http://hep.pa.msu.edu/~nadolsky/RhicBos)

$A_L(y_\ell)$ for different choices of min $p_{T\ell}$

$\Delta pp \to W^+ X$



$\Delta pp \to W^- X$



The direct experimental observable is $A_L(y_\ell)$ with $p_{T\ell} \geq p_{T\ell}^{\text{min}}$

Unpolarized W-boson charge asymmetry at the Tevatron

$$A_{charge}(y_\ell) \equiv \frac{\frac{d\sigma^{W^+}}{dy_\ell} - \frac{d\sigma^{W^-}}{dy_\ell}}{\frac{d\sigma^{W^+}}{dy_\ell} + \frac{d\sigma^{W^-}}{dy_\ell}}$$

- ✔ analog of $A_L(y_\ell)$ in the unpolarized case; related to

$$A_{charge}(y) = \frac{u(x_a)d(x_b) - d(x_a)u(x_b)}{u(x_a)d(x_b) + d(x_a)u(x_b)}$$

- ✔ constrains $d(x, M_W)/u(x, M_W)$ in CTEQ and MRST analyses

- ✔ published data is implemented in the global fit with the selection cut $p_{T\ell} \geq p_{T\ell}^{\text{min}} = 25$ GeV

$d\sigma/dy_\ell$ at the Born level

$$\left(\frac{d\sigma(p\bar{p}\to W^+X)}{dy_\ell}\right)_{LO} = \frac{2\pi\sigma_0}{S}\int_{y_{\min}(p_{T\ell}^{\min})}^{y_{\max}(p_{T\ell}^{\min})} dy\,\sin^2\theta$$
$$\times\left\{u(x_a)d(x_b)(1+\cos\theta)^2 + d(x_a)u(x_b)(1-\cos\theta)^2\right\},$$

with $x_{a,b} = \frac{Q}{\sqrt{S}}e^{\pm y}$, $\cos\theta = \tanh(y_\ell - y)$

- ✔ Simple kinematics due to $p_{TW} = 0$
- ✔ Only 2 structure functions $\propto (1\pm\cos\theta)^2$ in the W^+ rest frame
- ✔ $p_{T\ell}^{\min}$ appears only in the limits of the integration $y_{\min}$, $y_{\max}$

Similarly,

for $d\Delta\sigma/dy_\ell$:

$$\left(\frac{d\Delta\sigma(pp\to W^+X)}{dy_\ell}\right)_{LO} = \frac{2\pi\sigma_0}{S}\int_{y_{\min}(p_{T\ell}^{\min})}^{y_{\max}(p_{T\ell}^{\min})} dy\,\sin^2\theta$$
$$\times\left\{-\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2\right\}$$

NLO calculation of $d\sigma/dy_\ell$ is more complex

- ✔ 5 structure functions due to lepton-parton spin correlations
- ✔ complicated kinematics due to $p_{TW} \neq 0$
- ✔ integration of $p_T, y, Q^2, p_{T\ell}$ over experimental phase space (best done with Monte-Carlo integration)
- ✔ resummation of transverse momentum logarithms needed for p_T distributions
- ✔ is implemented in CTEQ analysis using an effective K-factor

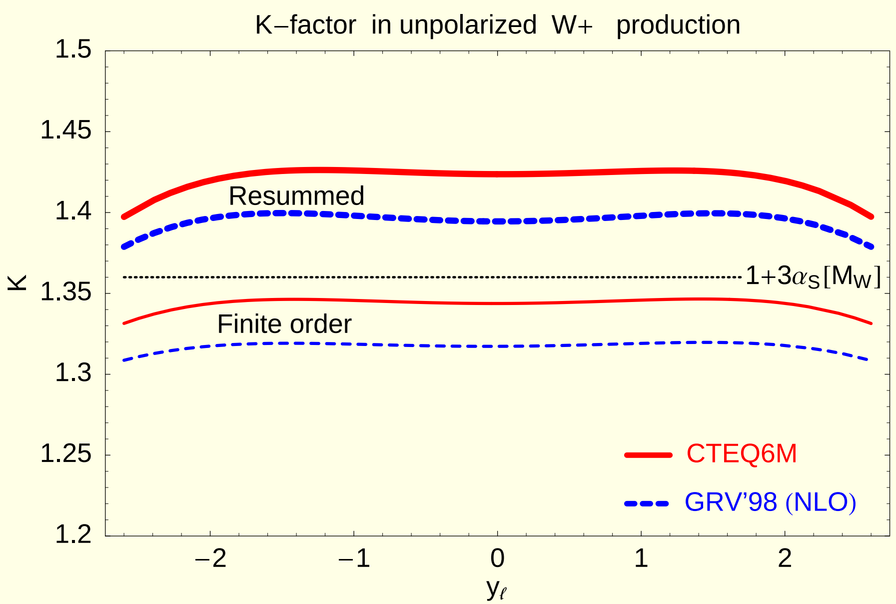
K-factor for $d\sigma/dy_\ell$ (PRELIMINARY)

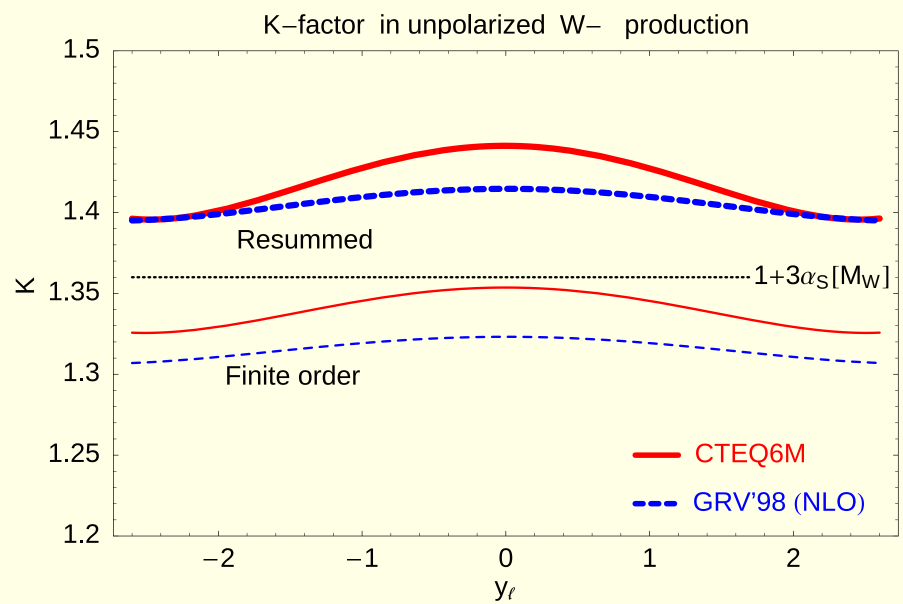
(Barger & Phillips, Collider Physics, ch. 7.11)

$$\frac{\frac{d(\Delta)\sigma_{NLO}}{dy_\ell}}{\frac{d(\Delta)\sigma_{LO}}{dy_\ell}} \approx \left(\underbrace{1+3\alpha_S(Q)}_{K_0} + \text{extra terms} \right)$$

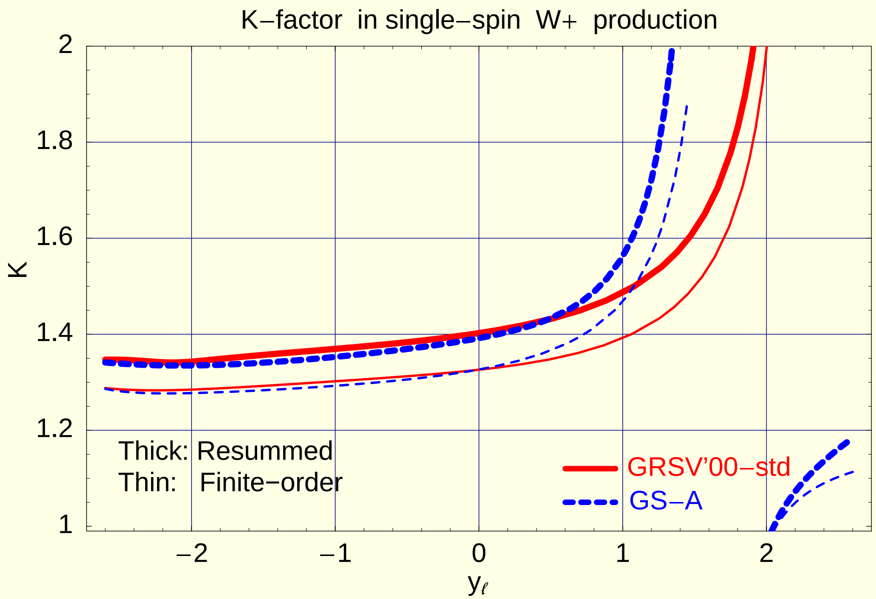
K_0 is independent of the PDF and spin ($K_0 \approx 1.36$ at $Q = M_W$)

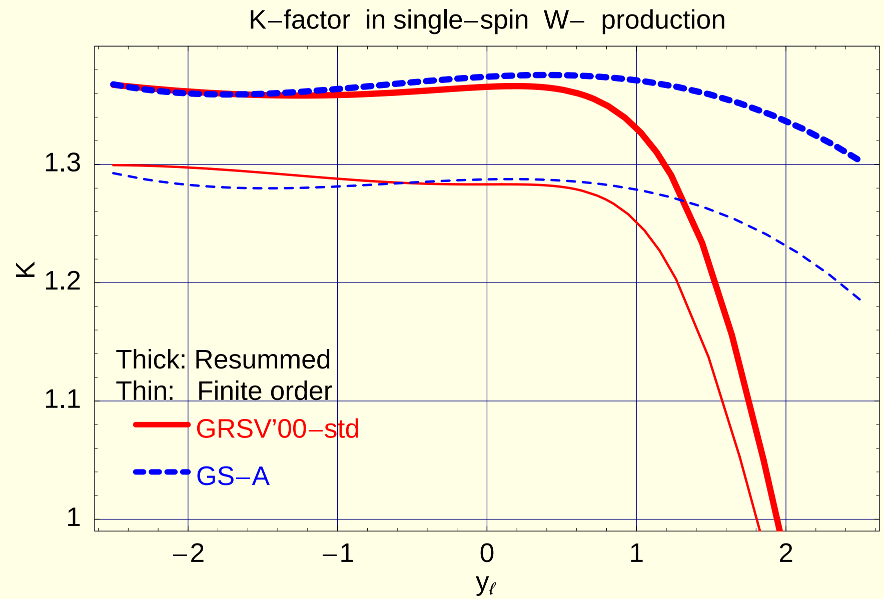
The extra terms depend on the PDF and spin; they are small in the unpolarized case

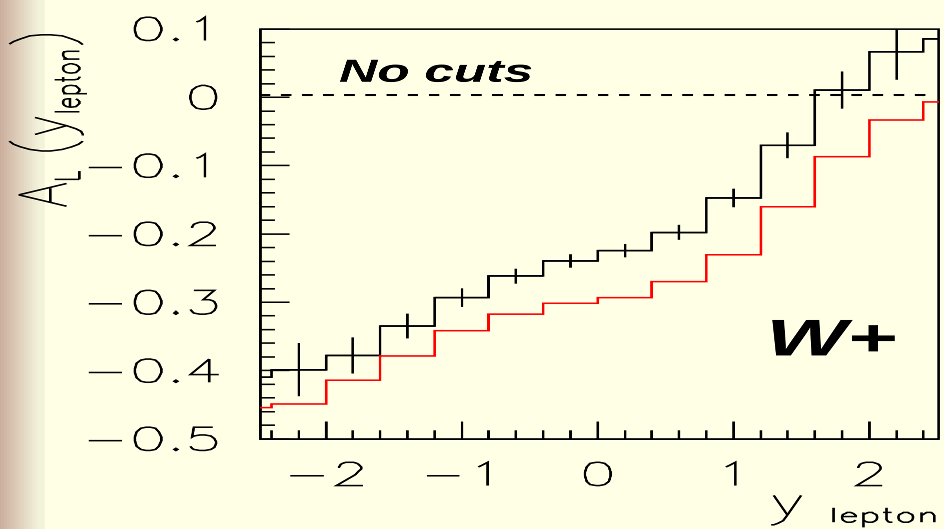


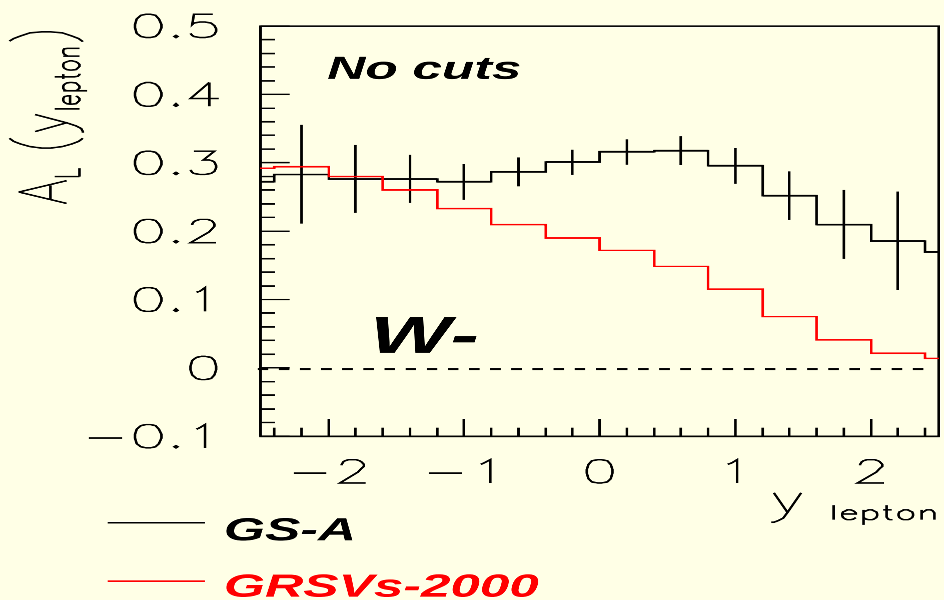


K-factors for $d\Delta\sigma/dy_\ell$ (PRELIMINARY)









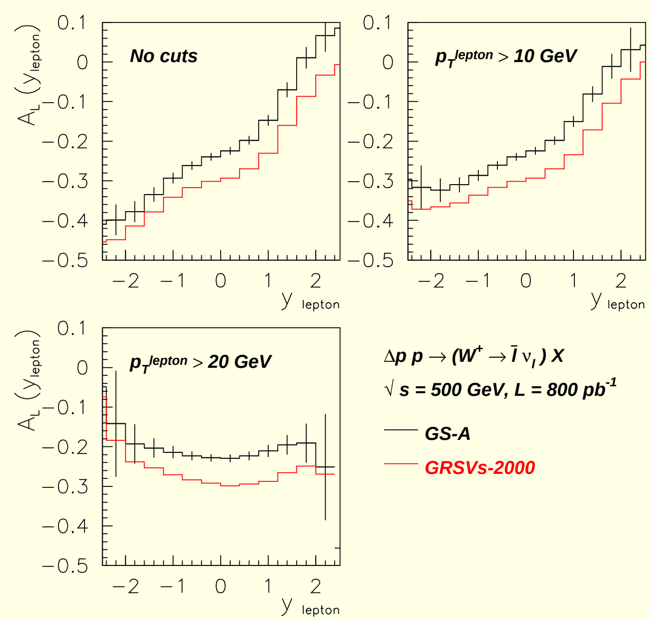
Spin-dependent K-factors diverge near the LO radiation zeros

Radiation zero: $$\left(\frac{d\Delta\sigma}{dy_\ell}\right)_{\mathrm{LO}} = 0$$

Is that a problem?

Radiation zeros...

- ✔ ...are easily identifiable in the data ($|A_L(y_\ell)| \lesssim 0.1$)
- ✔ ...are smeared by experimental resolution and statistical errors
- ✔ ...can be removed from the data by $p_{T\ell}$ cuts
- ✔ ...can be excluded from the fit by data selection cuts
- ✔ ...can be included in the fit, with the direct NLO calculation used only in the vicinity of the radiation zero
- ✔ no radiation zero for the cut $p_{T\ell} > 20$ GeV



Summary

1. The lepton single-spin asymmetry $A_L(y_\ell)$ provides a theoretically clean and direct observable in polarized W-boson production

2. Resummed $A_L(y_\ell)$ (with $p_{T\ell}$ cuts) can be easily implemented in the global fits using an effective K factor $K = \sigma_{NLO}/\sigma_{LO}$ and a simple procedure for handling radiation zeros

3. The K-factors (calculated in the p_T resummation formalism) for Gehrmann-Stirling, GRSV, and de Florian-Sassot PDF sets can be generated using RhicBos (input Xsection grids available by request)

Double Mellin transform

$$\sigma = \frac{1}{(2\pi i)^2} \int_{C_n} dn \int_{C_m} dm \Delta f_n \Delta f_m \widetilde{\sigma}(m,n),$$

where

$$\Delta f_m \equiv \int_0^1 dx\, x^{n-1} \Delta f(x)$$

is the n-th moment of $\Delta f(x)$,

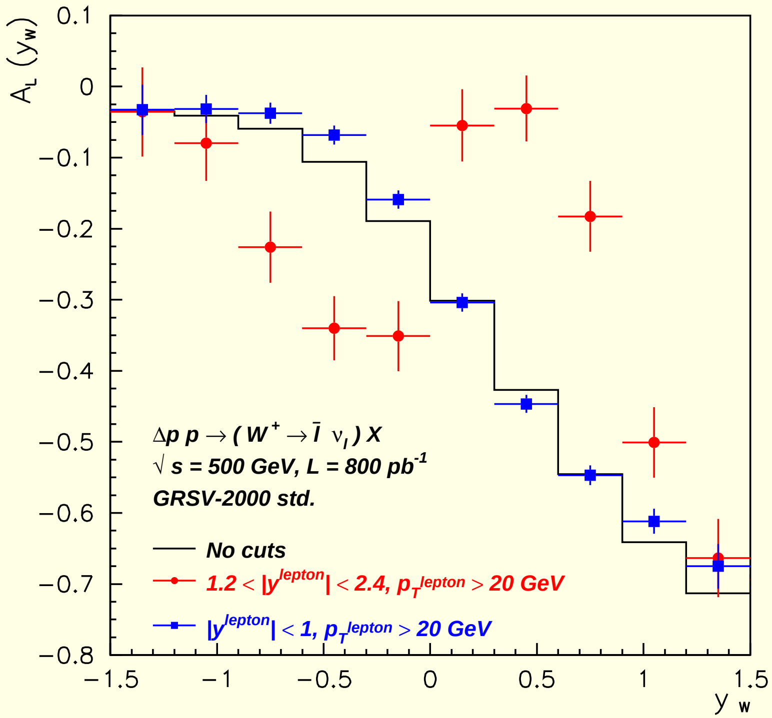
$$\widetilde{\sigma}(m,n) = \int d\{P.S.\} \int_0^1 dx_a \int_0^1 dx_b\, x_a^{-n} x_b^{-m} \frac{d\widehat{\sigma}(x_a, x_b)}{d\{P.S.\}}$$

is the convolution of the cross section $\sigma(x_a, x_b)$ (integrated over phase space P.S.) with the "eigenvector PDFs" x_a^{-m}, x_b^{-n}

$\sigma(m,n)$ can be calculated at the full NLO before the fitting

It is not obvious that $\int d\{P.S.\}$ can be evaluated using Monte-Carlo methods for complex m and n

Impact of leptonic cuts on the measurement of $A_L(y)$



Due to the spin-1 of $W^{\pm}$ boson, cuts affect the numerator and denominator of $A_L(y)$ differently

Interest in fully differential cross sections at the lepton level

✔ Partial angular coverage of Phenix and Star detectors

◇ $\not{E}_T$ and momentum of $W^\pm$ cannot be reconstructed

◇ y can be approximately reconstructed in a limited event sample and only if dynamics is well understood

◇

$$A_L(y)\Big|_{\substack{with\\lepton\\cuts}} \neq A_L(y)\Big|_{\substack{without\\lepton\\cuts}}$$

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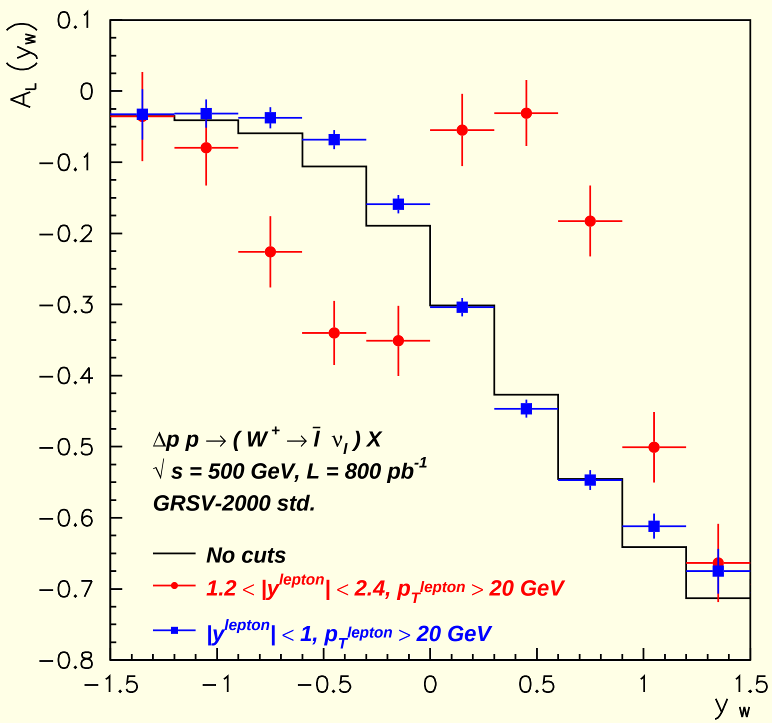
Impact of leptonic cuts on the measurement of $A_L(y)$



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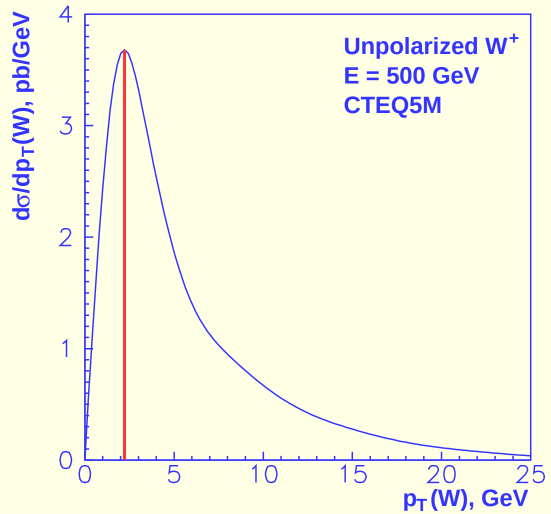
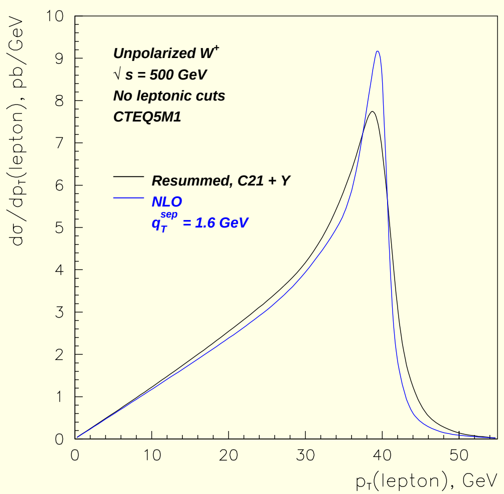
Transverse momentum distributions

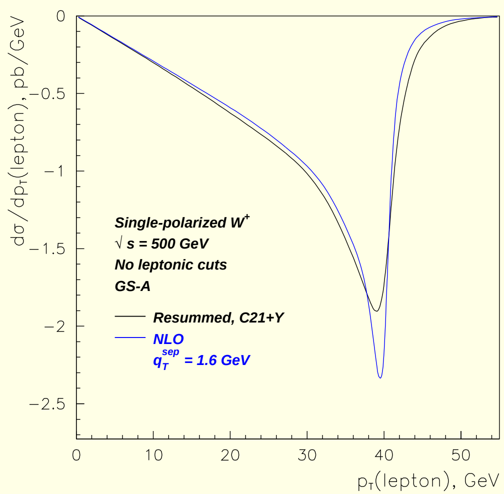


$p_{TW} \neq 0$! The shape of $d\sigma/dp_{TW}$ at $p_{TW} \to 0$ cannot be described at a finite order of PQCD: calculation of the sum

$$\frac{1}{p_{TW}^2}\sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n \sum_{m=0}^{2n-1} v_{mn}\left(\ln^m \frac{Q^2}{p_{TW}^2} \quad \text{or} \quad \delta(\vec{p}_{TW})\right)$$

is needed





Similar multiple parton radiation effects in lepton p_T distributions